Which Dual-Fuel Heat Pump Wins in the Cold? Comparative Performance of Sequential and Concurrent Heat Pump plus Furnace Configurations and Heat Pump Plus Boiler Configuration

Zhenning Li, Navin Kumar, Kyle Gluesenkamp, and Bo Shen
Oak Ridge National Laboratory, Oak Ridge, TN

ABSTRACT

This paper compares three dual-fuel heat pump (DFHP) configurations for residential space heating: (1) a conventional sequential heat pump plus furnace system that switches between electric and gas operation, (2) a seamlessly fuel-flexible heat pump (SFFHP) that allows concurrent heat pump and furnace operation, and (3) a hydronic DFHP that combines an air-to-water heat pump with a gas boiler and hydronic air handler. A building-equipment co-simulation framework is used to evaluate DFHPs across representative U.S. climate zones. Results show that smart dual-fuel control broadens the economic operating range of heat pumps relative to fixed switchover control. Case studies in multiple climate zones show that the conventional sequential DFHP provides a practical retrofit pathway in moderate climates, while the concurrent heat pump plus furnace system and heat pump plus boiler system deliver the largest utility-cost savings in cold climates, while avoiding reliance on electric resistance backup. The results identify climate-specific deployment pathways for dual-fuel technologies and show how grid-responsive control and system architecture influence operation cost benefits.

Keywords: heat pump, dual fuel, fuel flexible, boiler, furnace, hydronic, grid responsive

Introduction

Dual-fuel heat pumps (DFHPs) combine an electric heat pump with a gas-fired heating device so that a home can use the lower-cost or more capable heat source as outdoor conditions change. DFHP is especially attractive in existing homes because it can preserve the installed gas backup while extending heat-pump operation and avoiding major electrical upgrades. In practice, many fielded DFHPs still rely on a fixed balance-point temperature that switches the system from the heat pump to the furnace once the outdoor temperature falls below a preset value.

That conventional switching logic is simple, but it is not necessarily economical. It does not respond to time-varying electricity and gas prices, part-load performance, or situations in which partial gas assistance would allow the heat pump to operate more efficiently. Prior studies on smart controls and grid-interactive HVAC systems have shown that supervisory logic can

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change operating cost and system value (Alibabaei et al. 2017; Demirezen and Fung 2021; Fischer and Madani 2017; Siano 2014; Yu et al. 2019).

This paper focuses on three DFHP pathways with increasing control and system complexity. The first is a sequential heat pump-furnace configuration that still uses non-concurrent operation but applies smarter cost-based mode selection. The second is a seamlessly fuel-flexible heat pump (SFFHP) that allows the heat pump and furnace to operate concurrently, thereby splitting the required temperature lift and reducing compressor burden. The third is a hydronic DFHP that pairs an air-to-water heat pump with a gas boiler, enabling similar

concurrent operation on the water side. The goal is to compare performance and identify which DFHP pathway is most compelling for moderate, cold, and extreme-cold applications.

System Configurations and Control Concepts

Figure 1 illustrates the limitation of the conventional balance-point approach. Above the balance point, the heat pump supplies the full load. Below it, the system hands the entire load to the furnace. This mode-switching logic ignores hourly price signals and prevents either sub-system from contributing in the operating region where that sub-system performs best.

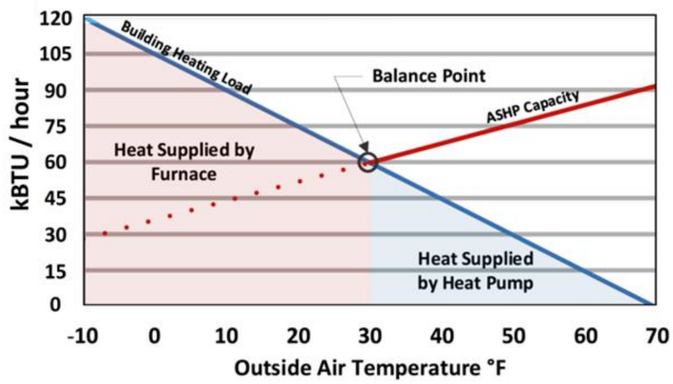


Figure 1. Conventional dual-fuel heat pump control based on a fixed balance-point temperature.

Figure 2 compares the two furnace-based hardware configurations considered in this study. The sequential DFHP uses the conventional ducted pairing of an indoor coil and furnace section, while the SFFHP enables concurrent operation so that the air is first heated by the heat pump and then topped off by the furnace. This arrangement reduces the temperature lift seen by the compressor and creates a continuous fuel-splitting decision rather than a binary mode switch.

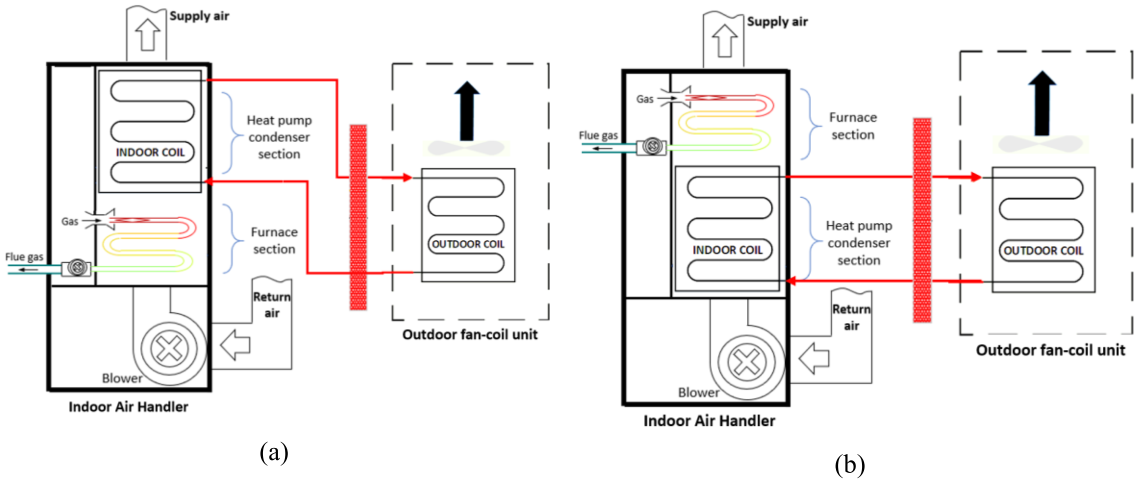


Figure 2. Furnace-based dual-fuel configurations: (a) conventional sequential heat pump-furnace system and (b) concurrent SFFHP configuration.

The hydronic concept shown in Figure 3 applies the same fuel-flexibility idea to a water loop. The air-to-water heat pump raises return water only to an intermediate temperature, and the boiler provides the final temperature lift needed by the hydronic air handler. The intermediate temperature becomes the control variable, allowing the system to preserve heat-pump efficiency while still meeting high supply-water-temperature requirements in severe weather.

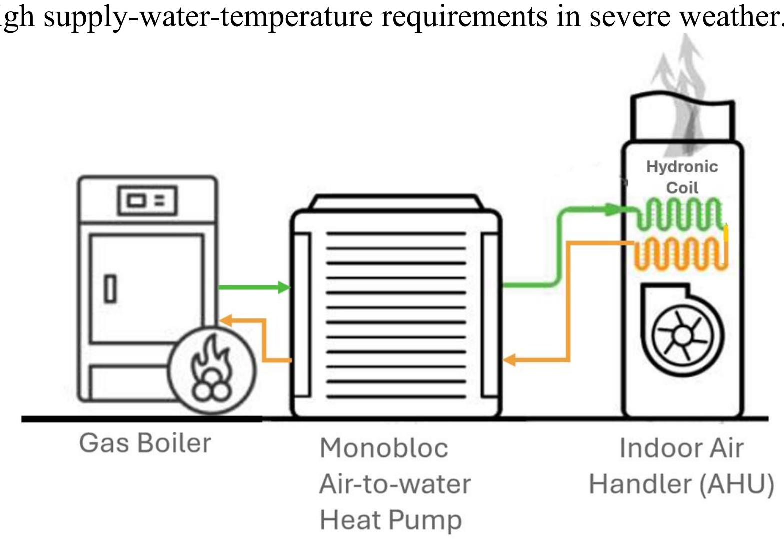


Figure 3. Hydronic dual-fuel heat pump concept using an air-to-water heat pump, gas boiler, and indoor air handler.

Methodology

Co-Simulation Framework

A co-simulation framework was developed to evaluate the DFHP concepts at the building and equipment levels. EnergyPlus provides building-load simulation, while equipment performance models predict heat pump and gas-device capacities, efficiencies, and control-dependent energy use. EnergyPlus Python plugin acts as a virtual thermostat and supervisory controller, exchanging information between the building model and equipment models at each timestep. This architecture makes it possible to compare conventional switching, smart sequential operation, and concurrent control under common weather and load conditions.

The workflow is shown in Figure 4. EnergyPlus calculates the space heating demand and indoor temperature response, while the controller selects the least-cost operating mode or gas-electric split based on hourly utility prices and equipment performance. For the hydronic DFHP, the air-to-water heat-pump boiler efficiency curves are implemented. The controller determines the optimal intermediate water temperature.

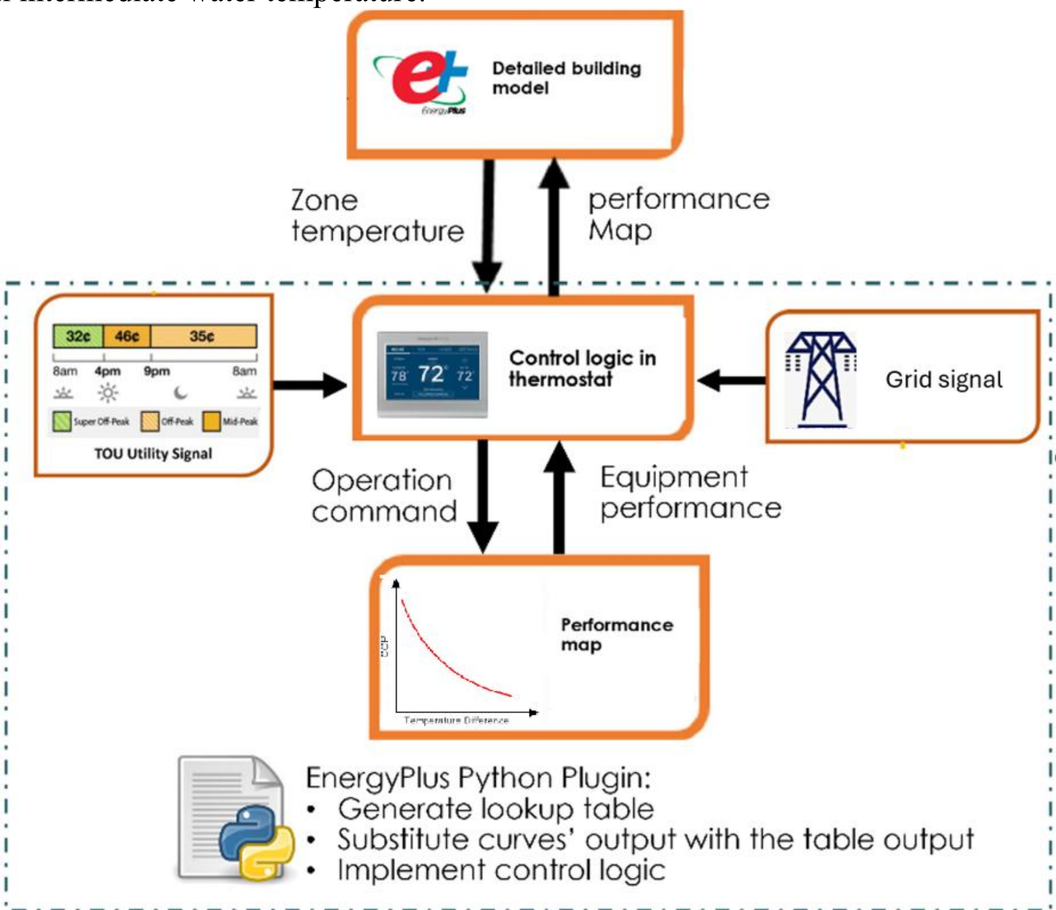


Figure 4. Building-equipment co-simulation framework integrating EnergyPlus, equipment performance models, and supervisory control.

Table 1 summarizes the system configurations simulated in this study, in which the first 3 systems are baseline system for reference.

Table 1. Heating-system configurations included in the comparison

System	Hardware concept	Control logic	Role in this study
80% AFUE gas furnace	Gas furnace only	Conventional thermostat	Reference baseline
95% AFUE gas furnace	High-efficiency gas furnace only	Conventional thermostat	Incremental gas-only upgrade benchmark

Electric heat pump + resistance	Air-source heat pump with supplemental electric resistance	Heat pump first; resistance only when needed	All-electric benchmark
Smart sequential DFHP	Ducted air-source heat pump paired with gas furnace	Hourly least-cost selection between heat pump and furnace	Retrofit-friendly dual-fuel pathway
Concurrent SFFHP	Heat pump and furnace in series to heat the air with optimized control	Optimal intermediate air temperature	Advanced dual-fuel pathway for cold climates
Hydronic DFHP	Heat pump and boiler in series to heat the water with optimized control	Optimal intermediate water temperature	Advanced dual-fuel pathway for cold climates

Equipment Models and Control Formulations

For the furnace-based DFHPs, a 3-ton cold-climate heat pump model is used in combination with a commercial gas furnace. The heat pump is based on validated ORNL work and is rated at 10.55 kW in heating mode under AHRI 210/240 conditions (AHRI 2008; Munk, Shen, and Gehl 2021). The gas furnace is modeled at 95% AFUE for the upgraded furnace and dual-fuel cases, while the reference furnace is modeled at 80% AFUE. The natural-gas energy density used in the simulations is 10.395 kWh/m^3.

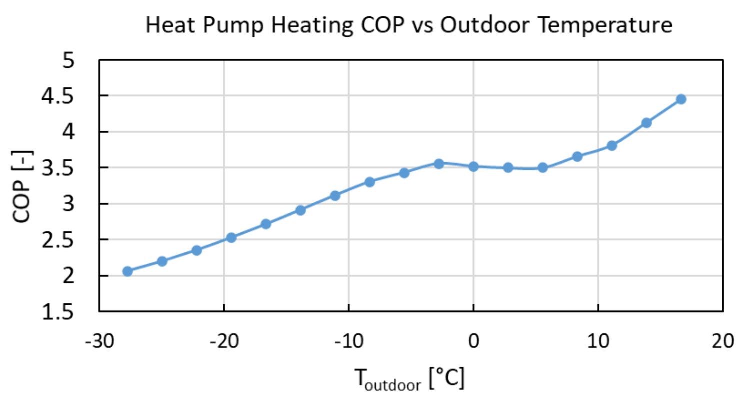


Figure 5. Heating COP of the 3-ton cold-climate air-source heat pump used in the furnace-based dual-fuel analysis.

For the hydronic DFHP, the boiler is modeled as an 80% AFUE non-condensing unit with a nominal 3-ton capacity. The air-to-water heat pump is characterized from OEM data at four leaving-water temperatures (95 °F, 113 °F, 131 °F, and 149 °F). Performance curves are fitted for compressor COP and heating capacity across common space heating operating envelope.

(a) (b)

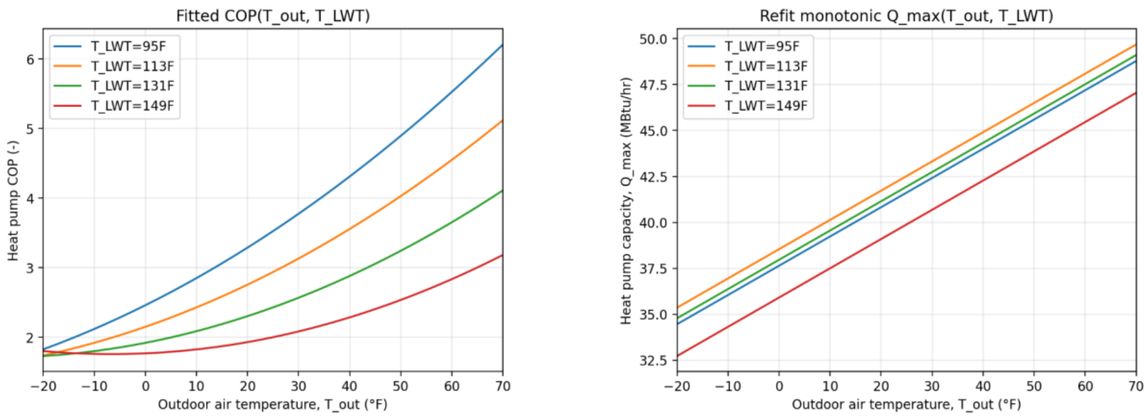


Figure 6. Fitted air-to-water heat pump performance surfaces for the hydronic DFHP: (a) compressor COP and (b) maximum heating capacity.

$$COP_{comp} = b0 + b1 \cdot T_{out} + b2 \cdot T_{out}^2 + b3 \cdot \Delta T + b4 \cdot \Delta T^2 + b5 \cdot (T_{out} \cdot \Delta T), \quad \text{where } \Delta T = (T_{LWT} - T_{out}) \qquad \text{Eq. 1}$$

$$Q_{max,comp} = a0 + a1 \cdot T_{out} + a2 \cdot T_{LWT} + a3 \cdot T_{LWT}^2 \qquad \text{Eq. 2}$$

Table 2 lists the fitted coefficients used in this study.

Table 2. Fitted coefficients for hydronic heat-pump COP and capacity surfaces

Model	Term	Coefficient
COP (Eq. 1)	1	5.416613
COP (Eq. 1)	Tout	0.052415
COP (Eq. 1)	T_{out}^2	-0.000252
COP (Eq. 1)	ΔT	-0.042787
COP (Eq. 1)	ΔT^2	0.000123
COP (Eq. 1)	$T_{out}\ \Delta T$	-0.000372
Q (Eq. 2)	1	8.422854
Q (Eq. 2)	T_{out}	0.159101
Q (Eq. 2)	T_{LWT}	0.524162
Q (Eq. 2)	T_{LWT}^2	-0.002280

When the hydronic heat-pump capacity is insufficient, supplemental electric resistance is on, then the effective COP is therefore calculated on a delivered-heat basis:

$$COP_{eff} = (Q_{comp} + Q\_{res}) / (Q\_{comp}/COP_{comp} + Q\_{res}) \qquad \text{Eq. 3}$$

The hydronic dual-fuel controller minimizes hourly utility cost by selecting the intermediate water temperature T_{mid}. With a fixed return water temperature of 120 °F and a required supply-water temperature $T_{SWT,req}$ defined by the outdoor-reset schedule, the heat-pump and boiler loads are split in proportion to the temperature lifts:

$$Q\_{HP} = Q_{load}\cdot(T_{mid} - T_{return})/(T_{SWT,req} - T_{return}), \quad Q_{boiler} = Q_{load} - Q\_{HP} \qquad \text{Eq. 4}$$

$$Cost = c_e\cdot E_{HP}\,(Q_{HP},T_{out},T_{mid}) + c_g\cdot(Q_{boiler}/\eta_{boiler})/100 \qquad \text{Eq. 5}$$

where c_e is the electricity price, c_g is the natural-gas price, and η_{boiler} is the boiler efficiency. The optimizer constrains T_{mid} between T_{return} and $T_{SWT,req}$ and enforces equipment capacity limits at each operating condition.

Case Studies

For the furnace-based systems, the analysis uses six representative cities spanning U.S. climate zones 3 through 8. Zones 1 and 2 are omitted because heating demand is comparatively small and dual-fuel operation is less relevant. Local electricity and natural-gas price assumptions are applied for each representative city.

Table 3. Representative cities used for the climate-zone analysis

Climate zone	Representative city
Zone 3	Los Angeles, CA
Zone 4	New York City, NY
Zone 5	Columbus, OH
Zone 6	Rochester, NY
Zone 7	Minneapolis, MN
Zone 8	Fairbanks, AK

The hydronic case study uses a representative single-family house heating demand derived from a Minnesota field-test house. The building load decreases approximately linearly with outdoor temperature and reaches zero at a balance-point temperature of about 62 °F. Required supply-water temperature is imposed through a hydronic outdoor-reset schedule so that supply-water temperature falls as outdoor conditions become milder.

(a) (b)

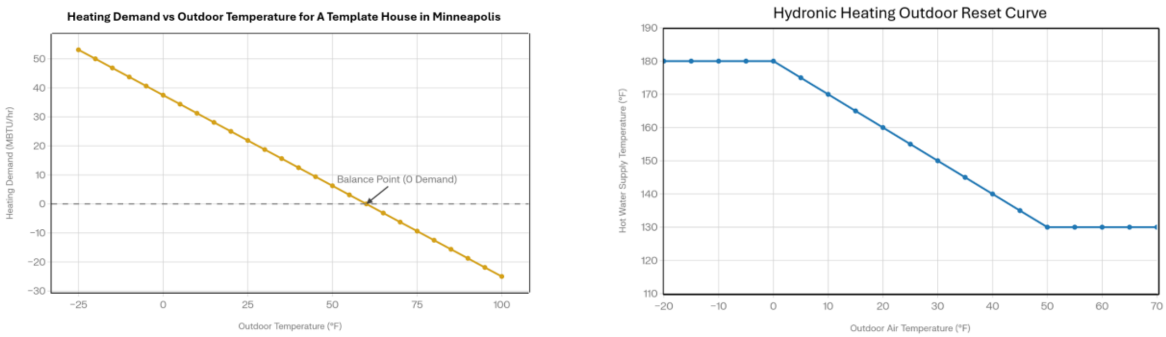


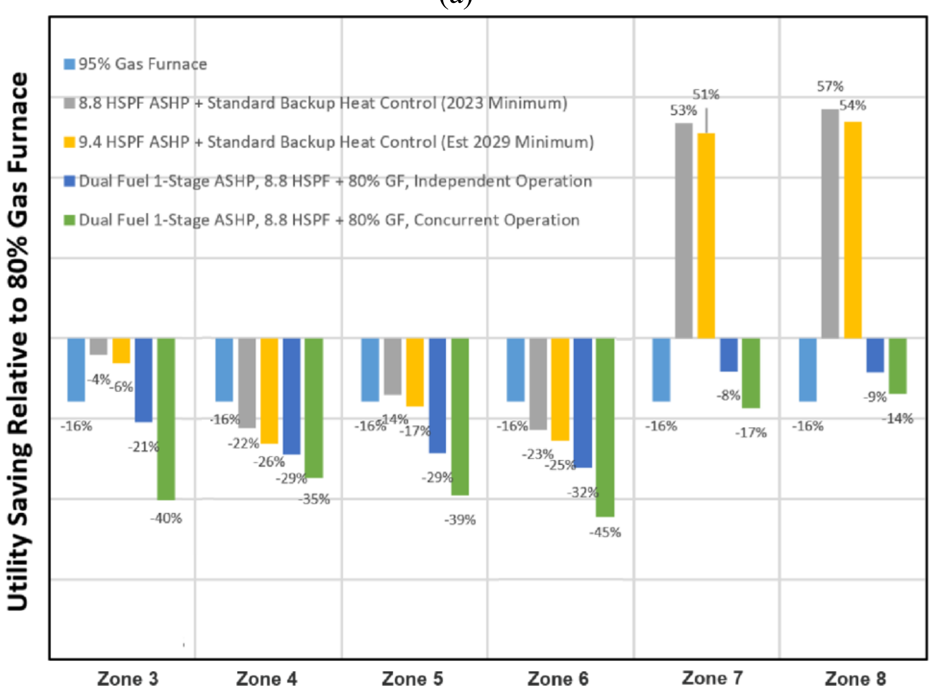
Figure 7. Hydronic case-study inputs: (a) representative Minneapolis house heating demand and (b) outdoor-reset schedule for required supply-water temperature.

Results and Discussion

Climate-Zone Comparison of Furnace-Based DFHPs

Figure 8 compares annual utility cost and primary energy consumption for the representative-city simulations. The benchmark is an 80% AFUE furnace. Additional comparisons are provided for a 95% AFUE furnace, two all-electric heat pumps with resistance backup, a smart sequential DFHP, and the concurrent SFFHP.

(a)



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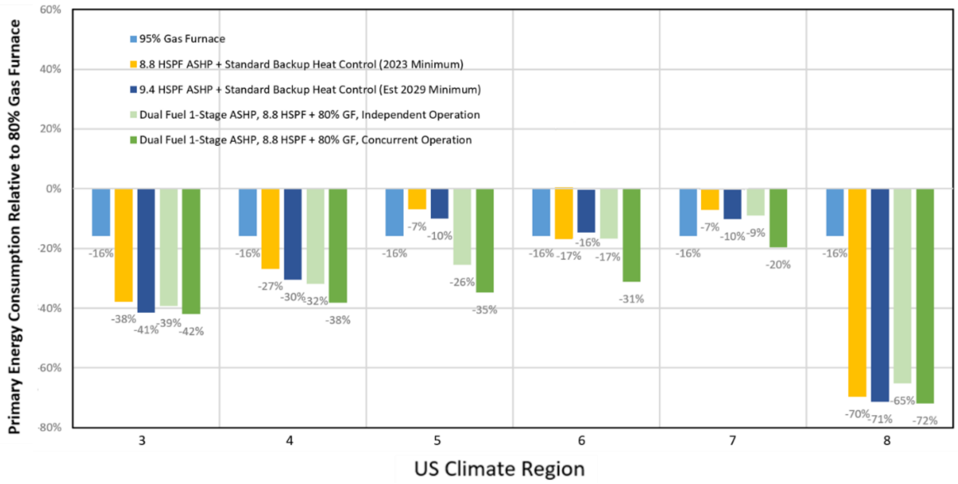


Figure 8. Representative-city comparison for the furnace-based systems: (a) annual utility-cost savings and (b) primary-energy savings, both relative to an 80% AFUE furnace.

Figure 8 (a) shows that all-electric heat pumps reduce utility cost in the moderate climates but lose advantage in the coldest zones because resistance becomes more prominent. And the smart sequential DFHP preserves cost savings across all climate zones because it can fall back on the gas furnace when heat-pump efficiency deteriorates. In addition, the concurrent SFFHP provides the strongest performance, delivering 14% to 45% annual utility-cost savings and the largest savings in the colder representative cities. Figure 8(b) shows that the same conclusion generally carries over to primary energy, with the dual-fuel heat pumps outperforming gas-only options and the concurrent configuration producing the largest primary energy reductions in the most severe climates.

These results demonstrate that the best dual-fuel configuration depends on climate. In moderate climates, a smart sequential DFHP already shows operation cost benefits while preserving comfort. In colder climates, concurrent SFFHP creates additional room for the heat pump to contribute economically not limited to a binary switchover to gas heat.

Where Concurrent Control Adds Value

The benefit of concurrent operation can be seen more explicitly in Figure 9, which maps hourly utility-cost savings from the SFFHP relative to the smart sequential DFHP as a function of outdoor temperature and the electricity-to-gas price ratio. The largest gains occur when outdoor temperature is low and electricity is expensive relative to gas. Under those conditions, a sequential controller would often shift entirely to the furnace, whereas the SFFHP can still use the heat pump for a portion of the lift and reserve the furnace for the final temperature rise. If electricity is sufficiently inexpensive, the heat pump dominates and blended operation is not necessary. If electricity is extremely expensive, gas heat dominates and the controller again approaches a single-fuel solution. The SFFHP is most valuable in the crossover region where neither fuel is uniformly optimal.

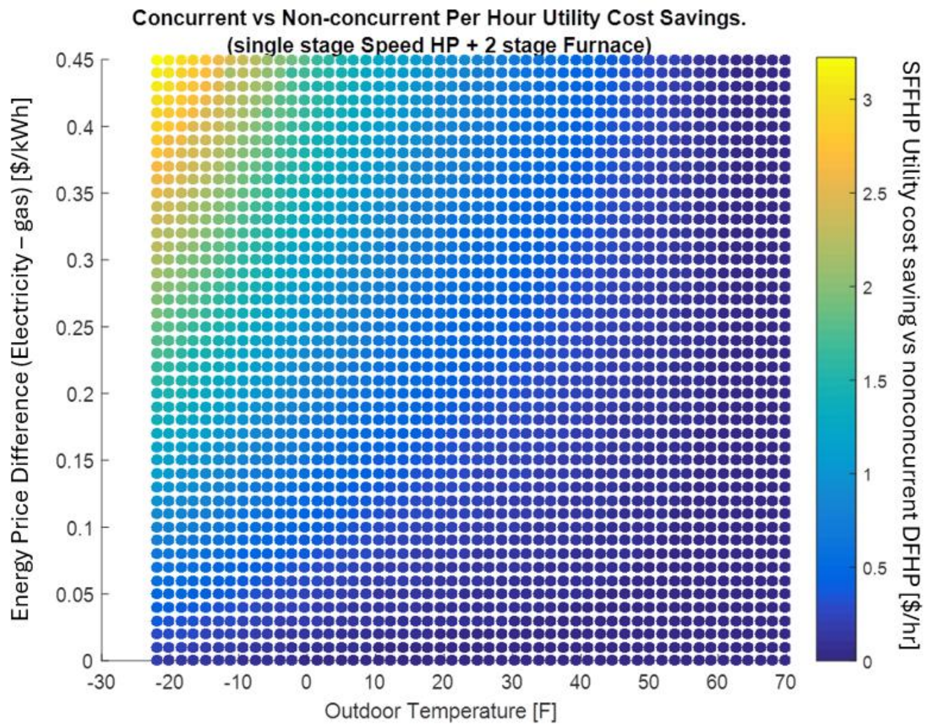
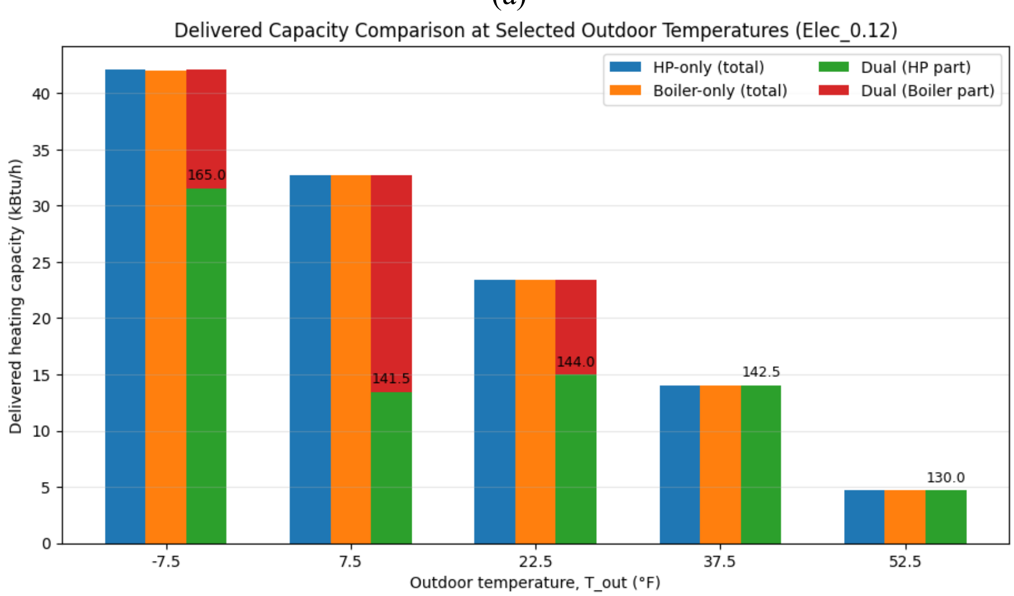


Figure 9. Hourly utility-cost savings from concurrent SFFHP operation relative to smart sequential DFHP operation.

Hydronic DFHP Performance in Severe Cold

In terms of hydronic DFHP, Figure 10 compares delivered heating capacity and hourly utility cost in Minneapolis for different operating modes, i.e., heat-pump-only, boiler-only, and optimal hydronic dual-fuel control.

(a)



(b)

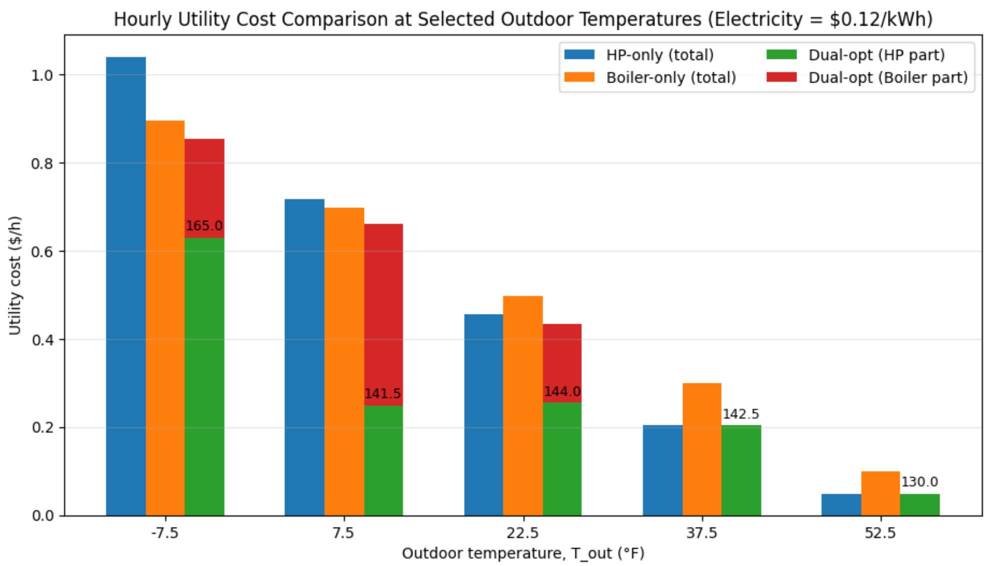


Figure 10. Minneapolis hydronic DFHP performance at selected outdoor temperatures: (a) delivered heating capacity and (b) hourly utility cost.

All the three modes can satisfy the space heating demand, but the cost-optimal split is different from one temperature to the next. At colder conditions, the controller assigns only part of the total lift to the heat pump and relies on the boiler for the high-temperature top-off. This prevents the heat pump from being forced to the highest leaving-water temperatures, where efficiency declines and supplemental resistance may be needed in the heat-pump-only case. At milder conditions, the optimal intermediate temperature moves closer to the return-water temperature, allowing the heat pump to supply a larger share of the load at favorable COP.

The cumulative effect is shown in Figure 11. The utility rates in Minneapolis are $0.12/kWh for electricity and $1.70/therm for natural gas, the hydronic dual-fuel controller reduces total seasonal heating cost by about 20% relative to heat-pump-only operation and by about 30% relative to boiler-only operation.

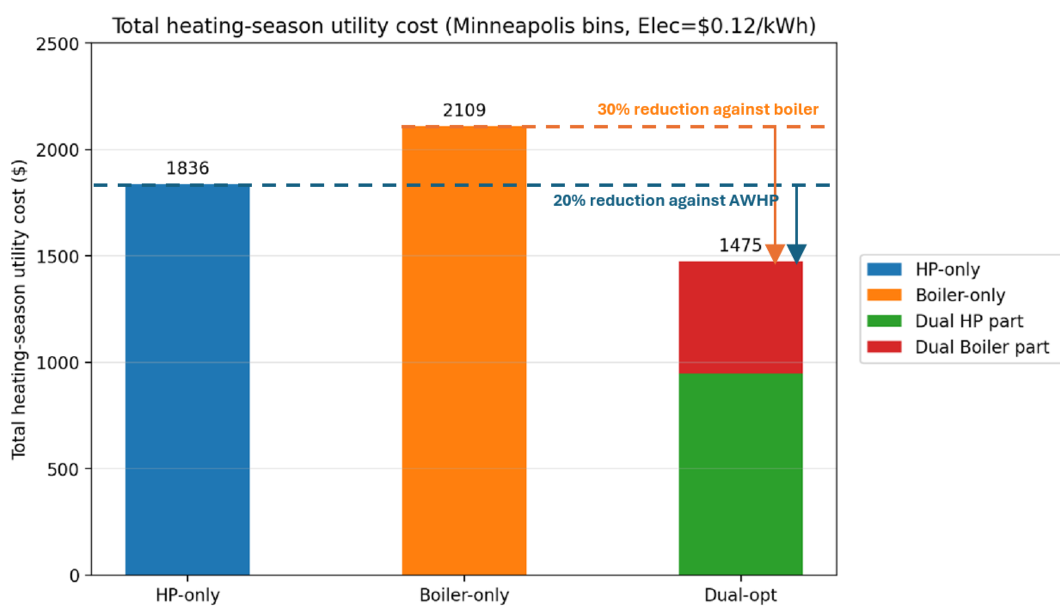


Figure 11. Total Minneapolis heating-season utility cost for heat-pump-only, boiler-only, and hydronic dual-fuel operation.

Figure 12 shows dual-fuel seasonal savings over a range of electricity and natural-gas prices. Figure 12 (a) compares the hydronic dual-fuel system with the more expensive single-system option between heat-pump alone and boiler-alone, while Figure 12 (b) compares it with the cheaper single-system option.

(a) (b)

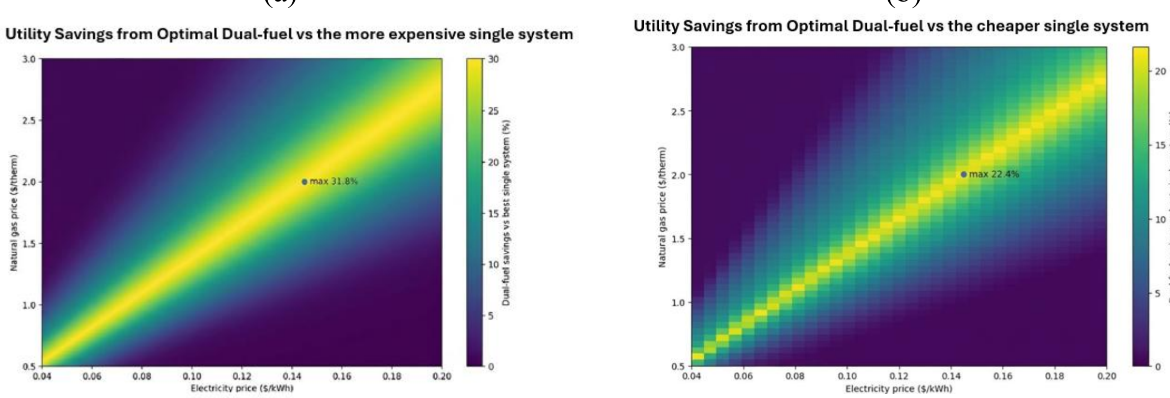


Figure 12. Hydronic dual-fuel seasonal utility-cost savings in Minneapolis relative to (a) the more expensive single-system option and (b) the cheaper single-system option.

The strongest value appears along the diagonal crossover region where gas and electricity are comparable on a delivered-heat basis. In that region, dual-fuel control can exploit the heat pump when lift is moderate and the boiler when marginal heat-pump cost rises, yielding savings as high as 31.8% versus the more expensive single-system alternative and 22.4% versus the cheaper one. Away from the diagonal, one fuel becomes dominant and the benefits of optimal controlled dual-fuel operation reduces.

Potential Deployment Pathways

Table 4 summarizes the potential deployment pathways for different dual fuel systems. It is worthwhile to mention that it only considers operation cost benefits without considering installation or retrofit cost.

Table 4. Climate-specific deployment pathways for operation cost reduction

Climate or application	Most compelling DFHP pathway	Primary rationale
Zones 3-5, existing ducted homes	Smart sequential DFHP (available on US market with smart thermostat)	Retains conventional furnace-backup architecture while improving operating cost through price- and performance-aware switchover control.
Zones 6,7,8, colder ducted applications	Concurrent HP + Furnace system or hydronic HP + boiler system (Both configurations are not available on US market yet)	Furnace or boiler provide the final high-temperature lift, reducing reliance on electric resistance backup while maintaining comfort.

Conclusion

This paper compares three residential dual-fuel heat-pump pathways: smart sequential heat pump and furnace control, concurrent heat pump plus furnace operation, and a hydronic heat pump plus boiler configuration. The analysis shows that conventional fixed switchover logic ignores hourly prices and the potential benefit of splitting temperature lift between electric and gas equipment.

For cold climate regions, the concurrent SFFHP and hydronic DFHP both provide a promising pathway. By optimizing the intermediate air temperature or water temperature, the controller assigns the low-to-moderate lift to the heat pump and reserves the furnace or boiler for the final lift. In the Minneapolis case study, the hydronic DFHP reduced seasonal heating cost by 20% relative to heat-pump-only operation and 30% relative to boiler-only operation while avoiding dependence on electric resistance backup. And the concurrent SFFHP yields annual utility-cost savings of up to 45% relative to the non-condensing furnace in cold regions.

For deployment, factors such as climates, utility structures, system complexity and retrofit constraints should be taken into consideration to decide the best system configuration. Future work should extend the comparison with installation and retrofit cost analysis and prototype validation with grid-responsive controls in residential homes.

Acknowledgment

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